Overview of the CLEO experiment

$D$ and $D_S$ leptonic decays to $\mu \nu$ and $\tau \nu$:
- Measurements of absolute branching fractions
- Measurements of absolute decay constants

Comparison with theory (LQCD)

Victor Pavlunin
on behalf of
the CLEO collaboration
DPF-2006
The CLEO detector

The CLEO detector was developed for $B$ physics at the $Y(4S)$. CLEO-III configuration:

- B-field: 1.5 T
- Gas (drift chamber): He and $C_3H_8$
- Tracking: 93% of $4\pi$, $\delta P/P = 0.6\%$ for a 1.0 GeV track
- Hadron particle ID: RICH (80% of $4\pi$) and $dE/dx$
- E/M crystal calorimeter: 93% of $4\pi$, $\delta E/E = 2.0\% (4.0)\%$ for a 1.0 GeV (100 MeV) photon
- Muon prop. chambers at 3, 5 and 7 $\lambda_I$.

Transition from CLEO III to CLEO-c:

- B-field: 1.5 T $\rightarrow$ 1.0 T
- Silicon vertex detector $\rightarrow$ low mass stereo drift chamber

Advantages of running at the $\psi(3770)$ for charm physics:

- Pure $DD$, no additional particles
- $\sigma[DD \text{ at } \psi(3770)] = 6.4 \text{ nb} \ [\sigma(cc) \text{ at } Y(4S) \sim 1.3 \text{ nb}]$
- Low multiplicity, high tagging efficiency (>20%)
The main task of the CLEO-c open charm program:

**Calibrate and Validate Lattice QCD**

- Help heavy flavor physics constrain the CKM matrix *now*:
  - Precision tests of the Standard Model or
  - Discovery of new physics beyond the SM in $b$ or $c$ quark decays

**Difficulty**: hadronic uncertainties complicate the interpretation of exp. results:

- Reduce theory error on B form factors and B decay constants using tested LQCD

- Help LHC search for and interpret new physics if new physics is strongly coupled *in the future*
Leptonic decays ($D^+ \to \mu \nu$ and $D_s \to \mu \nu$):

$|f_D|^2 |V_{CKM}|^2$

$\Gamma(D \to \pi \nu \nu)/\Gamma(D \to \mu \nu) \propto f_{D(s)}^2 |V_{cd(s)}|^2$

Semileptonic decays ($D \to \pi \nu \nu$, $D \to K \nu \nu$):

$|V_{CKM}|^2$

$|f(q^2)|^2$

$\Gamma(D \to \pi \nu \nu)/\Gamma(D \to \mu \nu) \propto |V_{cd(s)}|^2 |f_+(q^2)|^2$, where $q^2 \equiv M^2(eV)$

Combination of leptonic and semileptonic decays:

$\frac{\Gamma(D \to \pi \nu \nu)}{\Gamma(D \to \mu \nu)} \propto \frac{f_{D(s)}^2 |V_{cd(s)}|^2}{f_D^2}$
Results presented in this talk were obtained using the following data samples:

- \( \psi(3770) \): total luminosity = \( \sim 280 \text{ pb}^{-1} \)
- \( E_{\text{CM}} = 4170 \text{ MeV} \): total luminosity = \( \sim 200 \text{ pb}^{-1} \)

CLEO scanned \( E_{\text{CM}} = 3.97 - 4.26 \text{ GeV} \):

- Optimal energy for \( D_s \) physics: \( E_{\text{CM}} = 4.170 \text{ GeV} \)
- Dominant production mechanism: \( e^+ e^- \rightarrow D_s D_s^* \)

- [Additional 120 pb\(^{-1}\) at \( E_{\text{CM}} = 4170 \text{ MeV} \) already collected: to be analyzed]

Oct., 2006

Leptonic Charm Decays at CLEO
**Leptonic Charm Decays at CLEO**

**$D_\text{s}$ Leptonic Decays**

$$\Gamma(D^+ \rightarrow l^+\nu) = \frac{1}{8\pi} G_F^2 f_D^2 m^2_D (1 - \frac{m^2_l}{M_D^2})^2 |V_{cd}|^2$$

- **Standard Model predicts:**
  - $D$ decays: $\Gamma(e^+\nu) : \Gamma(\mu^+\nu) : \Gamma(\tau^+\nu) = 2.3 \times 10^{-5} : 1.0 : 2.7$
  - $D_s$ decays: $\Gamma(e^+\nu) : \Gamma(\mu^+\nu) : \Gamma(\tau^+\nu) = 2.5 \times 10^{-5} : 1.0 : 9.7$

- Use $V_{cd}$ and $V_{cs}$ to extract $f_D$ and $f_{D_s}$, and compare them to theory
$D^+ \rightarrow \mu \nu$ and $D^+ \rightarrow \tau \nu$ at the $\psi(3770)$

References:

PRL **95**, 25801 (2005)
PRD **73**, 112005 (2006)
Tagging at the $\psi(3770)$

- The $\psi(3770)$ is about 40 MeV above the $DD$ pair threshold ($\vec{P}_D = -\vec{P}_D$).

- Variables used in the tag reconstruction:
  
  $$M_{bc} = \sqrt{E_{\text{beam}}^2 - P_{\text{candidate}}^2}$$
  $$\Delta E = E_{\text{candidate}} - E_{\text{beam}}$$

- Leptonic decays are identified using missing mass squared:
  
  $$MM^2 = (E_{\text{beam}} - E_{\mu})^2 - (\vec{p}_{\text{tag}} - \vec{p}_{\mu})^2$$

Tagging creates a **beam of D mesons** with known momentum.
**D− Tags**

Cut on $\Delta E$ and fit $M_{BC}$:

- $K^+ \pi^- \pi^-$
- $K^+ \pi^- \pi^- \pi^0$
- $K_S \pi^-$
- $K_S \pi^- \pi^- \pi^+$
- $K_S \pi^- \pi^0$
- $K^+ K^- \pi^-$

Total number of tags: $158.4 \pm 0.5$ (stat) $\times 10^3$

<table>
<thead>
<tr>
<th>Mode</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \pi^- \pi^-$</td>
<td>$77387 \pm 281$</td>
</tr>
<tr>
<td>$K^+ \pi^- \pi^- \pi^0$</td>
<td>$24850 \pm 214$</td>
</tr>
<tr>
<td>$K_S \pi^-$</td>
<td>$11162 \pm 136$</td>
</tr>
<tr>
<td>$K_S \pi^- \pi^- \pi^+$</td>
<td>$18176 \pm 225$</td>
</tr>
<tr>
<td>$K_S \pi^- \pi^0$</td>
<td>$20244 \pm 170$</td>
</tr>
<tr>
<td>$K^+ K^- \pi^-$</td>
<td>$6535 \pm 95$</td>
</tr>
<tr>
<td>Sum</td>
<td>$158354 \pm 496$</td>
</tr>
</tbody>
</table>

Leptonic Charm Decays at CLEO
$D^+ \rightarrow \mu^+ \nu$ and $e^+ \nu$

- **Full event reconstruction:**
  - require a tag,
  - require a muon cand. ($E_{\text{CC}}^{\text{track}} < 300$ MeV),
  - veto events with extra tracks and energy clusters > 250 MeV.

- **Results:**
  - 50 $D^+ \rightarrow \mu \nu$ candidates
  - Estimated bckg: 2.8 events
  - $B(D^+ \rightarrow \mu^+ \nu) = [4.4 \pm 0.7 \text{(stat)} \pm 0.1 \text{(syst)}] \times 10^{-4}$
  - $f_{D^+} = [223 \pm 17 \text{(stat)} \pm 3 \text{(syst)}] \text{ MeV}$

- The same analysis is repeated for $D^+ \rightarrow e^+ \nu$. No signal candidates are seen: $B(D^+ \rightarrow e^+ \nu) < 2.4 \times 10^{-5}$ (at 90% CL)
Reconstruct $D^+ \rightarrow \tau^+ \nu$ with $\tau^+ \rightarrow \pi^+ \nu$

$[B(\tau^+ \rightarrow \pi^+ \nu)]$

MC: $D^+ \rightarrow \tau^+ (\pi^+ \nu)$

Broad MM$^2$

$B(D^+ \rightarrow \tau^+ \nu) < 2.1 \times 10^{-3}$ (at 90% CL)

$[SM: B(D^+ \rightarrow \tau^+ \nu) < (1.1 \pm 0.2) \times 10^{-3}$ (at 90% CL)]
$D_S \rightarrow \mu \nu$ and $D_S \rightarrow \tau \nu$ at $E_{CM} = 4170$ MeV

References:

CLEO CONF 06-17
hep-ex/0610026
Recall at $E_{CM} = 4170$ MeV: $e^+ e^- \rightarrow D_S D^*_S$

$D_S^*$ decays to $D_S$ via

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yields from M(Ds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ K^- \pi^+$</td>
<td>8446 ± 160</td>
</tr>
<tr>
<td>$K_S K^+$</td>
<td>1852 ± 62</td>
</tr>
<tr>
<td>$\eta \pi^+$; $\eta \rightarrow \gamma \gamma$</td>
<td>1101 ± 80</td>
</tr>
<tr>
<td>$\eta' \pi^+$; $\eta' \rightarrow \pi^+ \pi^- \eta$, $\eta \rightarrow \gamma \gamma$</td>
<td>786 ± 37</td>
</tr>
<tr>
<td>$\phi \rho^+$; $\phi \rightarrow K^+ K^-$, $\rho^+ \rightarrow \pi^+ \pi^0$</td>
<td>1140 ± 59</td>
</tr>
<tr>
<td>$\pi^+ \pi^- \pi^+$</td>
<td>2214 ± 156</td>
</tr>
<tr>
<td>$K^{*+} K^{<em>0}$; $K^{</em>+} \rightarrow K_S \pi^+$, $K^{*0} \rightarrow K^- \pi^+$</td>
<td>1197 ± 81</td>
</tr>
<tr>
<td>$\eta \rho^+$; $\eta \rightarrow \gamma \gamma$, $\rho^+ \rightarrow \pi^+ \pi^0$</td>
<td>2449 ± 185</td>
</tr>
<tr>
<td>Sum</td>
<td>19185 ± 325</td>
</tr>
</tbody>
</table>

Total number of tags from $M(D_s)$: $[19.2 \pm 0.3$ (stat)] $\times 10^3$
To fully reconstruct the event, the photon must be detected. The missing mass squared can be used to obtain the number of tags:

\[ MM^{*2} = (E_{CM} - E_{D_s} - E_{\gamma})^2 - (\vec{p}_{D_s} - \vec{p}_{\gamma})^2 \]

Total number of tags in the signal region of \( MM^{*2} \):

\[ [11.9 \pm 0.4 \text{ (stat)} \pm 0.5 \text{ (syst)}] \times 10^3 \]
\[ D_S \rightarrow \mu^+ \nu \text{ and } \tau^+(\pi^+ \nu) \nu \] (1)

- **Full event reconstruction:**
  - Require a tag and a \( \gamma \) from \( D_S^* \),
  - Require one additional track,
  - Veto events with \( E_{CC} > 300 \text{ MeV} \) or extra tracks.

- **Use** \( MM^2 \) to separate \( \mu^+ \nu \), \( \tau^+(\pi^+ \nu) \nu \) and background:
  \[ MM^2 = (E_{CM} - E_{D_S} - E_{\gamma} - E_{\mu(\pi)})^2 - (p_{\bar{D}_S} + p_{\bar{\gamma}} + p_{\bar{\mu}})^2 \]

- **Consider three cases:**
  - **Case I:** \( E_{CC}^{\text{track}} < 300 \text{ MeV} \) (accept 99% of muons and 60% of pions)
  - **Case II:** \( E_{CC}^{\text{track}} > 300 \text{ MeV} \) (accept 1% of muons and 40% of pions)
  - **Case III:** require an electron

[**Kinematical constraints are used to improve resolution and remove multiple combinations**]
$D_S \rightarrow \mu^+ \nu$ and $\tau^+(\pi^+ \nu) \nu$ (2)

Note the scale limits: 0.20 and 0.80 GeV$^2$

Sum of Case I and Case II

DATA

$\mu \nu + \tau \nu$ signal line shape

Consistency Check

100 events
\( D_S \rightarrow \mu^+ \nu \) and \( \tau^+(\pi^+ \nu) \nu \) (3)

- **Case I:**
  - 64 signal candidates, 2.0 bkg events:
  - \( B(D_S \rightarrow \mu^+ \nu) = [0.66 \pm 0.09\,\text{(stat)} \pm 0.03\,\text{(syst)}]\)%

- **Case II:**
  - 36 signal candidates, 4.8 bkg events:
  - \( B(D_S \rightarrow \tau^+ \nu) = [7.1 \pm 1.4\,\text{(stat)} \pm 0.3\,\text{(syst)}]\)%
  - \( [PDG-06: B(D_S \rightarrow \tau^+ \nu) = (6.4 \pm 1.5)\%] \)

- **Case III:**
  - **Use the SM \( B(\tau^+ \nu)/B(\mu^+ \nu) \) to average results above:**
  - \( B(D_S \rightarrow \mu^+ \nu) = [0.66 \pm 0.08\,\text{(stat)} \pm 0.03\,\text{(syst)}]\)%
  - \( [PDG-06: B(D_S \rightarrow \mu^+ \nu) = (0.61 \pm 0.19)\%] \)
  - \( f_{D_S} = [282 \pm 16\,\text{(stat)} \pm 7\,\text{(syst)}] \) MeV

- **Use the SM \( B(\tau^+ \nu)/B(\mu^+ \nu) \) to average results above:**
  - \( B(D_S \rightarrow \mu^+ \nu) = [0.66 \pm 0.08\,\text{(stat)} \pm 0.03\,\text{(syst)}]\)%
  - \( [PDG-06: B(D_S \rightarrow \mu^+ \nu) = (0.61 \pm 0.19)\%] \)
  - \( f_{D_S} = [282 \pm 16\,\text{(stat)} \pm 7\,\text{(syst)}] \) MeV

- **Case III:**
  - **No signal candidates:**
  - \( B(D_S \rightarrow e^+ \nu) < 3.1 \times 10^{-4} \)

**Electron Sample**

**Leptonic Charm Decays at CLEO**

Oct., 2006
Complimentary analysis:

\( D_S \to \tau^+ \nu \) with \( \tau^+ \to e^+ \nu \nu \).

\( \mathcal{B}(D_S \to \tau^+ \nu) \mathcal{B}(\tau^+ \to e^+ \nu \nu) \approx 1.3\% \) is large [cf. \( \mathcal{B}(D_S^+ \to Xe^+ \nu) \approx 8\% \)]

Analysis Technique:

- Find \( e^+ \) and \( D_S^- \) tag (\( \gamma \) from \( D_S^* \) is not reconstructed, same tag modes)
- Veto events with extra tracks
- Extra energy in CC < 400 MeV

Results:

\[ B(D_S \to \tau^+ \nu) = [6.3 \pm 0.8 \text{(stat)} \pm 0.5 \text{(syst)}] \% \]

[\( PDG-06: B(D_S \to \tau^+ \nu) = (6.4 \pm 1.5)\% \)]

\[ f_{D_S} = [278 \pm 17 \text{(stat)} \pm 12 \text{(syst)}] \text{ MeV} \]
Comparison with theory

Summary of CLEO-c results:

- \( f_{D^+} = [223 \pm 17(\text{stat}) \pm 3(\text{syst})] \text{ MeV} \)
- \( f_{D_s} = [280 \pm 12(\text{stat}) \pm 6(\text{syst})] \text{ MeV} \)

[Weighted average; syst. errors are mostly uncorrelated]

\( \frac{f_{D_s}}{f_{D^+}} = 1.26 \pm 0.11 \) Preliminary

CLEO-c: statistically limited

An example of theor. predictions:
Unquenched LQCD [PRL 95, 122002 (2005)]

- \( f_{D^+} = [201 \pm 3(\text{stat}) \pm 17(\text{syst})] \text{ MeV} \)
- \( f_{D_s} = [249 \pm 3(\text{stat}) \pm 16(\text{syst})] \text{ MeV} \)

\( \frac{f_{D_s}}{f_{D^+}} = 1.24 \pm 0.07 \)

LQCD: systematically limited
Conclusions

- An important task of CLEO-c is to calibrate and validate LQCD.
- Charm leptonic decays provide particularly stringent tests.
- Current precision of CLEO-c and LQCD results is comparable. CLEO-c results are statistically limited; LQCD results are limited by systematic uncertainties.
- Expect a three fold increase in the size of CLEO-c data sample and a complete suite of leptonic and semileptonic measurements in the next few years.
- On a longer time scale, BES III (China) should be able to improve CLEO-c results and further constrain the theory.
Additional Slides
The CLEO experiment is located at the Cornell Electron Storage Ring (CESR), a symmetric $e^+e^-$ collider that operated in the region of the Upsilon resonances for over 20 years:

- Max inst luminosity achieved: $1.3 \times 10^{33}$ cm$^{-2}$s$^{-1}$
- Total integrated luminosity at the Y(4S): 16 fb$^{-1}$
- Lots of important discoveries, e.g., $Y(nS)$, $b \rightarrow s\gamma$, $b \rightarrow uW$.

In 2003, CLEO started running at the \( \psi(3770) \), \(~40\text{ MeV above } D\bar{D} \text{ production threshold, and slightly higher energies for } D_S \text{ studies.} \)

Transition from CESR to CESR-c:

- 12 wigglers are installed to increase synchrotron radiation/beam cooling
- Max luminosity achieved: \(~7 \times 10^{31}\text{ cm}^{-2}\text{s}^{-1}\)
The main task of the CLEO-c open charm program:

- Calibrate and Validate Lattice QCD

- Help heavy flavor physics constrain the CKM matrix now:
  - Precision tests of the Standard Model or
  - Discovery of new physics beyond the SM in $b$ or $c$ quark decays

  **Difficulty:** hadronic uncertainties complicate interpretation of exp. results

A realistic example using recent CKM status (new $B_s$ mixing results are not included):

- Help LHC search for and interpret new physics (future)
C. Davies opened her talk in Lisbon at EPS-2005:
“There has been a revolution in LQCD…”

LQCD demonstrated that it can reproduce a wide range of mass differences and decay constants in unquenched calculations. These were postdictions.

Testable predictions are now being made for:
- Decay constants $f_D$ and $f_B$
- $D$ and $B$ Semileptonic form factors

CLEO-c can test $f_D$ and $D$ semileptonic form factors
Tagging at the $\psi(3770)$

- The $\psi(3770)$ is about 40 MeV above the $D\bar{D}$ pair threshold ($P_D = -P_{\bar{D}}$).
- One of the two $D$'s is reconstructed in a hadronic “tag” mode (e.g., $K^+\pi^-$). Two key variables:
  - $M_{bc} = \sqrt{E^2_{\text{beam}} - P^2_{\text{candidate}}}$
  - $\Delta E = E_{\text{candidate}} - E_{\text{beam}}$
- From the remaining tracks and showers the semileptonic decay is reconstructed (e.g., $K^-e^+\nu$).
- $U \equiv E_{\text{miss}} - |P_{\text{miss}}|$ is used to identify signal, where $E_{\text{miss}}$ and $P_{\text{miss}}$ are the missing energy and momentum approximating the neutrino $E$ and $P$. The signal peaks at zero in $U$.
- Full event reconstruction allows to measure any kinematic variable with no ambiguities and with high precision.

$\psi(3770) \rightarrow D^0 \bar{D}^0$

$\bar{D}^0 \rightarrow K^+\pi$, $D^0 \rightarrow K^-e^+\nu$
$D_S$ Tags at 4170

MC:
$D_S \rightarrow \phi\pi$

$e^+e^- \rightarrow D_S D_S^*$

$M_{BC} [GeV]$